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ELECTRON TRANSPORT THROUGH SINGLE AND MULTIPLE QUANTUM DOTS: THE FORMATION OF A ONE-DIMENSIONAL BANDSTRUCTURE

B. J. van Wees, L.P. Kouwenhoven, A. van der Enden,
and C.J.P.M. Harmans

*Faculty of Applied Physics, Delft University of Technology
P.O.Box 5046, 2600 GA Delft, The Netherlands*

C. E. Timmering

Philips Research Laboratories, 5600 JA Eindhoven, The Netherlands

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We describe transport experiments performed on ballistic submicron devices which are defined in the two dimensional electron gas of GaAs/AlGaAs heterostructures by means of metallic gates. Conductance measurements on single quantum dots reveal the formation of magnetically induced zero-dimensional (0D) states. In an array of 15 coupled quantum dots, these 0D-states develop into a 1D bandstructure.

1. Introduction

In the field of semiconductor physics, the electron transport through ballistic conductors has attained much attention in the last few years¹. With a variety of fabrication techniques it has become possible to make impurity-free submicron conductors in which the electron transport is denoted as ballistic. Moreover, when the dimensions of the conductor are comparable to the De Broglie wavelength λ_F of the electrons at the Fermi energy, quantum phenomena become important. In this case, the electron transport is called quantum ballistic, which will be the main subject of this paper.

One of the first results obtained in the quantum ballistic transport regime is the conductance quantization of a quantum point contact (QPC)². A QPC is a short ballistic constriction with variable width defined in a two dimensional electron gas (2DEG). On changing the width of the constriction it was found that at zero-magnetic field the conductance changes in quantized steps of $2e^2/h$. This result is a demonstration of transport through 1D subbands which are formed due to the lateral confinement in the constriction. Changing the width moves the Fermi energy relative to the 1D subbands and each time the number of occupied subbands changes by one, the conductance changes by $2e^2/h$.

An appealing theoretical formalism to describe the conductance quantization and many other transport phenomena is the Landauer-Büttiker formalism³. The 1D subbands are viewed here as 1D current channels, each current channel contributing $T 2e^2/h$ to the conductance. A fully transmitted current channel (which has a transmission probability $T=1$) from the source reservoir to the sink reservoir then contributes the quantized value $2e^2/h$ to the conductance. The Landauer-Büttiker formalism has also become important to describe transport in the quantum Hall

effect (QHE) regime. When the Fermi energy is located between two Landau levels in the bulk of the 2DEG, the relevant electron states for transport (those at the Fermi energy) are located at the boundaries of the sample⁴. These so-called edge states or edge channels follow equipotential lines at the boundaries of the 2DEG, and electrons which move in edge channels at opposite boundaries have opposite velocities. The transport through edge channels is 1D and each spin-resolved channel contributes e^2/h to the Hall conductance. If N_L Landau levels are occupied in the bulk, also N_L edge channels carry a net current, which yields a total Hall conductance of $G_H = N_L e^2/h$. It was pointed out by Büttiker³ that due to the separation of left- and right-going edge channels at opposite boundaries of the sample, backscattering involves scattering from one sample edge to the opposite edge. When the Fermi energy is between two Landau levels in the bulk, this backscattering is suppressed because of the absence of available extended electron states. Experiments by Komiyama et al.⁵, van Wees et al.⁶, and Alphenaar et al.⁷ have shown that forward scattering between edge channels at the same boundary can also be extremely small. On short distances of order μm this forward scattering can be virtually absent, for which reason edge channels can be treated as independent 1D current channels. Recent theoretical⁸ and experimental⁹ work has suggested that the edge channel picture may be valid to describe transport in the fractional quantum Hall effect regime as well.

The one-dimensionality of the transport, in combination with the absence of scattering, make edge channels an ideal starting point to study the 0D-regime. In the subsequent sections the formation of magnetically induced 0D-states in a single quantum dot¹⁰, and the formation of a 1D band structure in a periodic array of coupled quantum dots¹¹ will be discussed.

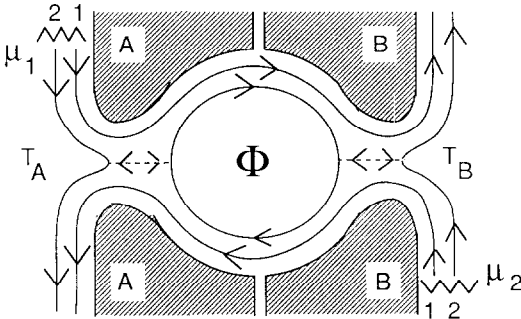


Figure 1. Schematic layout of the quantum dot with diameter of $1.5\mu\text{m}$ and two 300nm wide quantum point contacts. The electron flow in edge channels is shown when a high magnetic field B is applied. A 1D loop is formed which encloses a flux Φ , when an edge channel is only partially transmitted by both quantum point contacts.

2. Transport through a single quantum dot.

The device is defined in the 2DEG of a high mobility GaAs/AlGaAs heterostructure. The 2DEG has an electron density of $2.3 \cdot 10^{15}\text{m}^{-2}$ and a transport mean free path of $9\mu\text{m}$. On top of the heterostructure two pairs of metallic gates A and B are fabricated by means of electron-beam lithography (see fig.1). Application of a negative voltage of -0.2V on the gates, depletes the electron gas underneath the gates and creates a quantum dot in the 2DEG with a diameter of $1.5\mu\text{m}$. To allow electron transport, a connection from the two wide 2DEG regions to the quantum dot is arranged by two 300nm wide QPCs. The narrow channel between the two gate pairs A and B is already pinched-off at this gate voltage. Applying the gate voltage to only one gate pair and zero voltage to the other, defines a single QPC in the 2DEG. In this way the transport properties of the individual QPCs can be measured and be compared to that of the complete device. The conductance measurements are performed at a temperature of 10mK , in a high magnetic field ($>1\text{T}$), by biasing a small current through the sample ($<1\text{nA}$) and by measuring the resulting voltage between the two wide 2DEG regions.

In ref.12 we have used the gate geometry of fig.1 to study how the conductance G_D of the two QPCs in series is related to the conductances G_A and G_B of the individual QPCs. At zero-magnetic field, we found a simple Ohmic addition $1/G_D = 1/G_A + 1/G_B$ ¹³. However, when a magnetic field is applied, an enhancement of the series conductance was observed, and above 1T the series conductance became equal to the smallest conductance of one of the individual QPCs: $G_D = \min(G_A, G_B)$. In this case, scattering processes between edge channels are completely absent and the transport is called adiabatic (i.e. electrons travel through the device with conservation of quantum-edge channel-number). The important consequence of adiabatic transport is that edge channels can be treated as independent 1D current channels.

The location of two independent edge channels in the quantum dot is schematically shown in fig.1 The first edge channel is completely transmitted through the total device and therefore contributes e^2/h to the conductance. The

second edge channel is only partially transmitted through the two QPCs with probabilities T_A and T_B . Inside the dot this edge channel forms a 1D loop, which encloses a magnetic flux $\Phi = BA$, with A the enclosed area. The contribution of the second edge channel to the conductance is equal to $T_2 e^2/h$, where the transmission probability T_2 of the confined edge channel loop is given by:

$$T_2 = \frac{T_A T_B}{1 - 2 \sqrt{R_A R_B} \cos(\nu) + R_A R_B} \quad (1)$$

with $R=1-T$ and the phase ν is defined by $\nu = 2\pi\Phi/\Phi_0$ where $\Phi_0 = h/e$ is the fluxquantum. The total conductance G_D is just the sum of all the contributions and is given for M completely transmitted edge channels by:

$$G_D = \frac{e^2}{h} (M + T_2) \quad (2)$$

Eqs. 1 and 2 imply that when the enclosed flux Φ is changed the conductance oscillates with a period equal to the fluxquantum Φ_0 .

Eq.1 is known to describe a 1D interferometer, which consists out of two barriers with transmission probabilities T_A and T_B placed at a distance a . For that case, the phase ν is given by $\nu = 2\pi(2a/\lambda_F)$. When ν is an integer times 2π , constructive interference occurs between the two barriers which results in maximal total transmission T_2 (when $T_A = T_B$ and $\nu = \text{integer} \cdot 2\pi$, it follows from eq.1 that $T_2 = 1$). This fact that the total transmission can be larger than the transmissions of the individual barriers, is known as resonant tunneling. By changing the phase ν , one can tune the interference from constructive to destructive (or the transmission T_2 from maximal to minimal) just like in an optical interferometer. In terms of energy, the electron states between the two barriers split up due to the finite length a , resulting in single electronic 0D-states. When the Fermi energy coincides with a 0D-state the transmission T_2 becomes resonant. The observation of 0D-states at $B=0$ has been reported by Smith et al.¹⁴ who were able to vary the distance a between the two barriers, and by Hirayama and Saku¹⁵ who varied the Fermi energy. In our approach using edge channels, the 0D-states are formed when the enclosed flux Φ is an integer times the fluxquantum Φ_0 ¹⁶. The advantage of this approach is that scattering in the dot is absent and that the confined edge channels are 1D by themselves.

Fig.2a shows G_D versus B at constant $V_g = -0.35\text{V}$ in the transition region between the second to the third plateau, which corresponds to the complete transmission of two (spin resolved) edge channels and the partial transmission of the third channel. Large oscillations are seen between the two plateaus with an amplitude modulation up to 40% of e^2/h . Fig.2b displays the oscillations on an expanded scale showing their regularity. The period B_0 of the oscillations smoothly varies from $B_0 = 2.5\text{mT}$ at $B = 2.5\text{T}$ to $B_0 = 2.8\text{mT}$ at $B = 2.7\text{T}$. This period cannot be deduced directly from the enclosed area A , because the location of the edge channels at the boundary also depends on B ¹⁰. In fig.2c the region of low transmission or weak coupling is plotted. Here the conductance is $2e^2/h$ (the third edge channel is completely reflected here), except when the Fermi energy coincides with the energy of a 0D-state. The narrow conductance

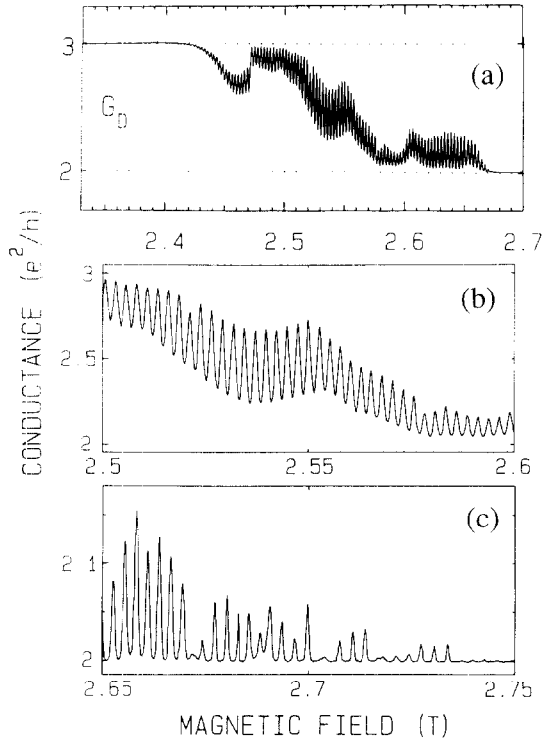


Figure 2. (a) Transition from the second to the third plateau of the dot conductance G_D , showing large oscillations with amplitudes up to 40% of e^2/h . (b) Enlarged oscillations from (a) showing their regularity (period $B_0=2.5\text{mT}$). (c) Region of low transmissions of the third edge channel ($T_A, T_B=0$). The discrete conductance peaks demonstrate resonant transmission through 0D-states.

peaks demonstrate the resonant transmission through 0D-states. It is shown elsewhere¹⁰ that a calculation of G_D from eq.1 with the measured conductances of the individual QPCs substituted for the transmissions T_A and T_B , gives good agreement with the measured G_D shown in fig.2. In fig.3 it is demonstrated that the phase ν can also be varied by changing the area of the dot. Here G_D is measured as a function of gate voltage for a fixed $B=2.5\text{T}$. In fig.3a the voltage is varied on both gates (which affects the total area of the dot) and the oscillation period is 1mV. In fig.3b the voltage on one gate pair is kept fixed and varied on the other (which affects only half of the dot area) and, as expected, the oscillation period is now 2mV.

The above measurements demonstrate that the conductance of a quantum dot in a high magnetic field can be strongly modulated by changing the magnetic flux enclosed by the current carrying states. If the Fermi energy coincides with the energy of a 0D-state, the transmission through the dot is at resonance. The rounded oscillations for large transmissions T_A and T_B and the sharp peaks for low T_A and T_B illustrate the effect of coupling of the discrete 0D-states with the continuum of states in the 1D edge channel in the wide 2DEG regions outside the dot, which can be shown to be in accordance with eq.1.

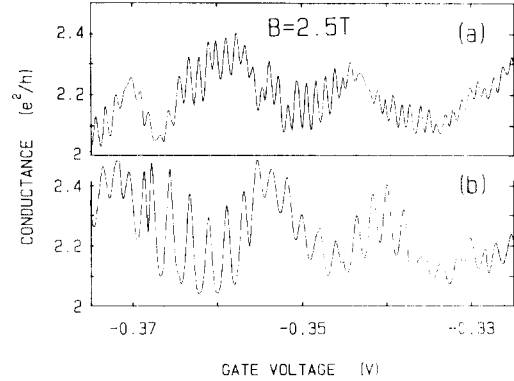


Figure 3. Conductance oscillations as a function of gate voltage for a fixed magnetic field $B=2.5\text{T}$. In (a) the voltage on both gate pairs is varied (period=1mV) and in (b) the gate voltage on one pair is kept fixed at -0.35V and varied on the other gate pair (period=2mV).

3. Transport through multiple quantum dots

One of the basic principles of solid state theory is that when atoms are put together in a periodic array, the discrete atomic states develop into collective states: the band structure. A similar band structure can also be expected when quantum dots, in which 0D-states are formed as described in the previous section, are placed in a periodic array. We have realized such a device acting as an artificial 1D crystal which will be discussed in this section.

The gate geometry of the 1D crystal device is shown schematically in the inset of fig.6. The ungated 2DEG of this sample has an electron density of $2.7 \cdot 10^{15}\text{m}^{-2}$ and a transport mean free path of $10\mu\text{m}$. A voltage V_{g1} on the first gate defines in total 16 fingers in the 2DEG at a period of 200nm. The effect of making the voltage V_{g2} more negative is to increase the depletion region around the second gate. This reduces the area of each dot and lowers the Fermi energy in the conducting regions. The potential landscape in the 2DEG presumably resembles a smooth periodic electrostatic confinement, with the asymmetric saddle-shaped maxima defined by the fingers.

The transport through a finite periodic 1D potential has been calculated by different authors using different methods¹⁷. We have extended eq.1 to a recursive formula describing the transmission probability T_N of N barriers in series¹¹:

$$T_N = t_N t_N^*; \quad t_N = \frac{t_{N-1}}{1 - r_{N-1} \exp(i\nu)} \quad (3)$$

In fig.4 T_N is plotted as a function of phase for 16 barriers and for three different transmissions T of the individual barriers. Due to the coupling (expressed by T), the 0D states develop into bands characterized by a high transmission T_N . They are separated by gaps with low T_N . The bands consist of a number of discrete states equal to the number of quantum dots $N-1$. As can be seen also in fig.4, weak coupling results in large gaps (tight binding regime), while strong coupling yields small gaps (nearly free electron regime).

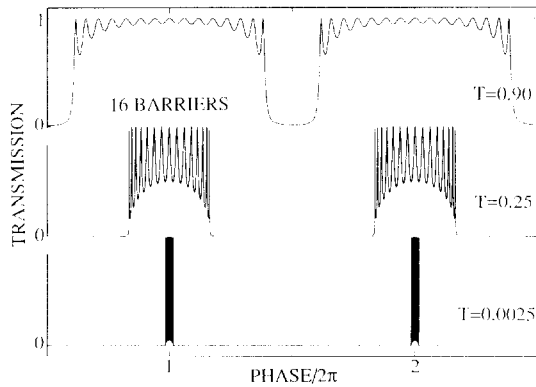


Figure 4. Transmission T_N versus phase $v/2\pi$ of a periodic 1D chain of 16 barriers, for different single barrier transmissions T .

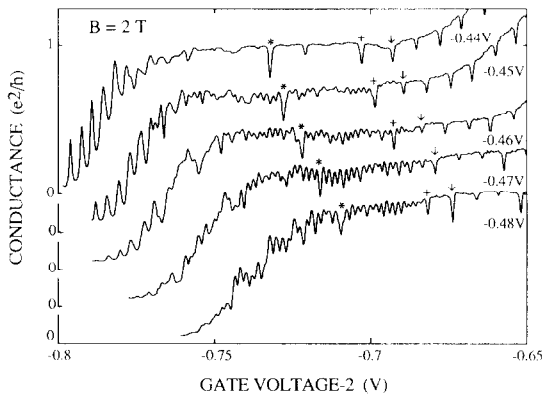


Figure 5. Conductance as a function of gate voltage V_{g2} on the second gate at a fixed magnetic field of 2 T and for different values of gate voltage V_{g1} on the first gate. Corresponding peaks are marked. The curves have been offset for clarity.

The conductance measurements in this section are performed at 10mK and at a fixed magnetic field of $B=2T$. Fig.5 shows the first quantum Hall plateau for several fixed values V_{g1} and changing the voltage V_{g2} on the second gate. Large oscillations are seen below the first plateau (i.e. $G < e^2/h$), and in the plateau region deep downward peaks enclose smaller oscillations. Some of the deeper peaks are marked, to indicate their shift when the voltage V_{g1} is varied. The plateau region of the curve $V_{g1}=-0.45V$ is measured and shown enlarged in fig.6. As can be seen, the two deeper peaks enclose 15 smaller oscillations, which corresponds exactly to the number of quantum dots.

This simple counting comparison between the number of oscillations and the number of quantum dots, shows that the observed oscillations can be associated with the formation of a band structure in the periodic 1D crystal device. The deeper peaks correspond to the energy gaps

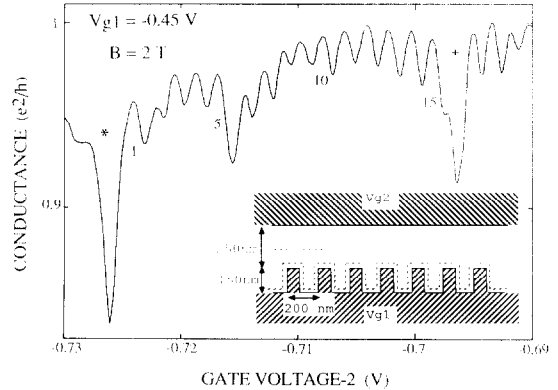


Figure 6. Conductance as a function of gate voltage V_{g2} on the second gate at 2 T and $V_{g1} = -0.45V$ on the first gate. The inset schematically shows the gate geometry; the dashed lines indicate the depletion regions in the 2DEG.

and the smaller oscillations to the discrete states, which form the bands. Going vertically through fig.4, one can also see that when the transmissions T are varied relatively fast compared to the phase v , the Fermi energy moves through the band structure. This situation corresponds to the large oscillations below the first plateau, where T changes from 0 (at pinch-off) to 1.

The effect of irregularities on the bandstructure can also be seen in fig.5. The trace of $V_{g1} = -0.46V$ shows 16 smaller oscillations between the marks "*" and "+", and in the curve of $V_{g1} = -0.47V$ the gap marked by "+" is not seen. Note also the smaller oscillations on the left of the mark "*" indicating another band, although clearly less regular. The 16 oscillations between two gaps cannot be explained by the number of quantum dots, not even when they are considered to be unequal. An additional scatterer somewhere in the device could be the cause of this extra oscillation. The disappearance of a gap is presumably due to irregularities, which introduces mixing between bands. This also follows from further calculations¹¹ of the transmission T_N from eq.3 for $N=16$, in which irregularities are introduced by variations in the transmissions T of the individual barriers. With one barrier chosen in the middle of the crystal of which T deviates by a few percent, the calculations show that the smaller oscillations group together in pairs of two, very similar as seen in some parts of fig.5.

5. Conclusions

The state of the art of submicron technology has reached the level where one is able to study fundamental solid state phenomena as for instance 1D transport, 0D-states, and artificial band structures. These phenomena can be visualized in transport measurements in a very simple way, and can be described by physically transparent theories as the Landauer-Büttiker formalism.

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